Dairy Diet Phosphorus Effects on Phosphorus Losses in Runoff from Land-Applied Manure

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ABSTRACT

Phosphorus losses from land-applied manure can contribute to nonpoint source pollution of surface waters. Dietary P forms and levels influence P concentrations in animal manures and may affect P losses from land-applied manure. The objective of this study was to determine the effects of dairy diet P concentration on P losses in runoff from land-applied manure. Dairy manures from two dietary P levels were applied (24 May 1999) at 56 wet Mg ha^{-1} to a silt loam soil, to provide 40 and 108 kg P ha^{-1}, respectively. The high P diet manure was also applied at 21 wet Mg ha^{-1} (40 kg P ha^{-1}) to provide a P rate equivalent to the low P diet manure. Plots were subjected to simulated rainfall (75 mm h^{-1}) just prior to corn (*Zea mays* L.) planting in June and again after harvest in October 1999. Runoff was analyzed for dissolved reactive P (DRP), bioavailable P (BAP), total P (TP), and sediment concentration. Natural runoff from the same plots was collected from November 1999 through July 2000 and analyzed for DRP. At equivalent manure rates, DRP concentration in June runoff from the high P diet manure was ≈10 times higher (2.84 vs. 0.30 mg L^{-1}) than the low P diet manure, and four times higher (1.18 vs. 0.30 mg L^{-1}) when applied at equivalent P rates. Phosphorus concentrations in October runoff and November to July natural runoff were lower (0.02 to 1.69 mg L^{-1}), but treatment effects were the same as for the June runoff. These results show that excessive addition of inorganic P to dairy diets increases the potential for P loss in runoff from land-applied manure, even at the same P application rate. Diet P effects on potential losses in runoff from land-applied manure should be considered in P-indexing and nutrient management planning.

Phosphorus loss in runoff from cropland is an environmental concern because this P often promotes weed and algae growth in lakes and streams. When these weeds and algae die and decompose, dissolved O_2 levels in lakes and streams are depleted, which can lead to odors, death of fish, and a general degradation of the aesthetic and recreational value of the environment (Daniel et al., 1994; Sharpley et al., 1994; Carpenter et al., 1998).

Phosphorus from land-applied manure is one of the major sources contributing to soil P accumulation in Wisconsin, and there is increasing evidence that the amount of P in manure could be substantially reduced by avoiding excess P supplementation of dairy rations (Ternouth, 1989; Morse et al., 1992; Metcalf et al., 1996; Khorasani et al., 1997). Satter and Wu (1999) reported that the average dairy diet in the USA is supplemented to contain 4.8 g P kg^{-1}, while only 3.8 g P kg^{-1} is needed for optimum milk production and reproductive efficiency. This is a 25% over-supplementation of dietary P, based on National Research Council standards (National Research Council, 1989). Valk et al. (2000) discussed the possibility of decreasing P in dairy cow diets without negatively affecting performance and reproductive ability, and cited the work of Brodison et al. (1989) showing that dietary P could be lowered from 6.5 to 4.5 g P kg^{-1} without consistently influencing milk production or reproductive performance. One study has shown that a 40% decrease in dietary P lowered excreted P by 23% (Morse et al., 1992), and another study reported that reduced dietary P levels lowered P excretion by 30% (Metcalf et al., 1996).

Phosphorus excretion in manure depends largely on the level of P intake (Ternouth, 1989; Morse et al., 1992; Metcalf et al., 1996; Khorasani et al., 1997). If P supplementation could be reduced to the minimum concentration needed for optimum production, the amount of P in manure and in applications to farmland would also decrease. Studies are needed to determine if reducing P supplementation in dairy diets, and the resulting decrease in manure P concentrations, will reduce P concentrations in runoff when manure is land-applied. The objective of this study was to determine dairy diet P effects on the amounts and forms of P in manure as well as on P losses in runoff from land-applied manure. To relate this work to on-farm manure management practices, we included a manure application strategy simulating a N-based nutrient management approach where manures from two P diets were applied at the same manure rate. In addition, a P-based nutrient management approach was also included where manures from the differing P diets were applied to achieve the same P addition.

MATERIALS AND METHODS

Dairy (*Bos taurus*) diet P effects on P losses in runoff in no-till corn (*Zea mays* L.) were determined in a field experiment at the University of Wisconsin Agricultural Research Station at Arlington (43°17′N, 89°22′E). Four different manure treatments, based on two dietary P levels and including a control, were applied to a Ringwood silt loam soil (fine-

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Abbreviations: BAP, bioavailable P; CV, coefficient of variation; DI, water soluble P; DRP, dissolved reactive P; HPD-21, high P diet manure applied at 21 wet Mg ha^{-1}; HPD-56, high P diet manure applied at 56 wet Mg ha^{-1}; LPD-56, low P diet manure applied at 56 wet Mg ha^{-1}; TP, total P.

loamy, mixed, mesic, Typic Argiudolls). Phosphorus was determined in runoff from simulated and natural rainfall events.

Dairy manures (feces only, no bedding) with differing P concentrations were hand applied to 2.4-m × 2.4-m plots on 24 May 1999. The experimental site was not tilled in 1999 and residue from the previous year's corn crop remained on the surface. As described below, simulated rain was applied from 1–4 June 1999 and again on the same plots on 30 Sept., 1, 4, and 5 Oct. 1999 after corn silage harvest. Natural runoff was collected from November 1999 to July 2000.

A randomized complete block design with four replications was used in the experiment. The four treatments were: control (no manure, no P addition); low P diet (LPD-56) manure (4.8 g P kg^{-1} manure dry matter) and high P diet (HPD-56) manure (12.8 g P kg^{-1}) applied at 56 wet Mg ha^{-1} to provide 40 and 108 kg P ha^{-1}, respectively; and high P diet manure applied at 21 wet Mg ha^{-1} (HPD-21) to provide the same P addition (40 kg P ha^{-1}) as LPD-56.

Feces were collected from lactating Holstein cows involved in a study designed to determine effects of dietary P levels on milk production and reproductive performance (Wu et al., 2000). For dairy, almost all P excreted is in feces with only trace amounts of P in urine (McDowell, 1992). In this paper, we use the term manure to describe the fecal portion of the dairy manure collected for use in this study. Manure was collected from the barn floor immediately after voiding from Days 148 to 155 during the 308-d full lactation study. Manure from individual cows fed either the low or high P diet was collected and composited in buckets, immediately frozen, and stored at 0°C until it was thawed at the time of field application. The low P diet group was fed no supplemental P, while the high P diet group had monosodium phosphate added to the low P diet. This resulted in low and high dietary P levels of 3.1 and 4.9 g P kg^{-1}, respectively. The low and high dietary P levels produced manures with average P concentrations of 4.8 and 12.8 g P kg^{-1}, respectively. These manure P concentrations, assessed from samples collected in the barn, were used to calculate manure application rates in the field experiments. Samples of manure applied to each plot in the LPD-56 and HPD-56 treatments (n = 8) were collected and analyzed to determine the actual P additions (Table 1).

Samples of manure from each diet were dried at 70°C, ground to pass a 2-mm sieve, and analyzed for TP, water soluble P (DI), and BAP. Manure subsamples were ashed (500°C, 24 h), the ash collected in HCl, and analyzed colorimetrically (Schulte et al., 1987) to determine TP. We shook 0.250 g manure in 25 mL deionized water for 1 h and analyzed the filtered extract using the ascorbic acid method (Murphy and Riley, 1962) to determine DI. To determine BAP, we used the iron-oxide paper strip method (Sharpley, 1993) with a 0.125-g manure sample extracted by shaking with 40 mL of 0.005 M $CaCl_2$ for 24 h with five 2- × 10-cm strips.

Soil samples for antecedent moisture and soil P determinations were collected from the 0- to 2-cm soil depth. This depth was used since it represents the reactive zone for the soil-simulated rain interface (Sharpley et al., 1994). These samples were obtained by compositing ten soil cores from the area immediately adjacent to, but outside the simulated rain test areas in each plot. Soil moisture was determined by weighing the samples before and after drying. Soil test P levels in each plot were obtained by analysis of soil samples dried at 32°C and ground to pass a 2-mm sieve. Surface residue cover (corn stover and manure) was measured inside each plot frame before simulated rainfall using the pin drop method (Morrison et al., 1996). The slope of each plot was also measured using a level placed on the edges of the plot frames. Soil P tests included distilled water extraction (Pote et al., 1996), Mehlich III (Mehlich, 1984), Bray-Kurtz P-1 (Frank et al., 1998), and BAP (Sharpley, 1993). Soil BAP was determined by shaking 1.0 g of soil with 40 mL of 0.005 M $CaCl_2$ for 24 h with five 2- × 10-cm iron-oxide strips. Phosphorus in the extracts obtained by each method was determined colorimetrically by the ascorbic acid method (Murphy and Riley, 1962). Ammonium oxalate P, iron (Fe), and aluminum (Al) (Pierzynski, 2000) were determined by inductively coupled plasma optical emission spectrometry (ICP-OES, Iris Plasma Spectrometer, Thermo Jarrell Ash Corp., Franklin, MA), and P saturation percentage was calculated as the oxalate-extractable P divided by the sum of the oxalate-extractable Al and Fe content, and multiplied by 100 (Pote et al., 1996).

Table 1. Phosphorus components of dairy manure applied to field plots, June 1999.

Manure	Total P	Water soluble P	Bioavailable P	Dry matter
	g P kg^{-1}			g kg^{-1}
High P diet	**8.9**	**3.6**	**6.1**	**160**
Low P diet	**4.9**	**1.4**	**2.1**	**150**
		ANOVA		
$P > F$	**<0.01**	**<0.01**	**<0.01**	**0.31**
LSD (0.05)	**0.8**	**0.6**	**0.1**	**NS†**
CV, %	**5.4**	**11.4**	**1.1**	**5.1**

† NS, not significant.

Simulated rainfall was applied to experimental treatments using techniques similar to those described by Zemenchik et al. (1996). A portable, multiple intensity rainfall simulator (Meyer and Harmon, 1979) equipped with a Veejet 80150 nozzle (Spraying Systems, Wheaton, IL) located 3 m above the soil surface delivered an application rate of 75 mm h^{-1} with a corresponding energy of 0.278 MJ ha^{-1} mm^{-1}. This rainfall intensity has an approximate recurrence interval of ≈50 yr (Huff and Angel, 1992). Steel plot frames (91-cm length × 91-cm width × 30-cm height) were set in the soil to a 15-cm depth in a representative area of each plot before simulated rain was applied. Runoff was collected at the downslope side of the plot frame and continuously removed using a 0.02-MPa vacuum (Dixon and Peterson, 1968) and placed in a holding tank.

Runoff samples were collected and total runoff volumes were recorded 30 min after runoff initiation and 60 min after the start of rainfall. Since time to runoff initiation was not significantly affected by treatments and treatment effects were similar at both times, only 30-min data are presented in this paper. After mixing to resuspend sediment, subsamples of the runoff were obtained for sediment, DRP, BAP, and TP determinations. The subsample for DRP determination was filtered (0.45-μm pore diam.) immediately in the field. Unfiltered runoff samples were analyzed for TP using the ammonium persulfate and sulfuric acid digestion method (USEPA, 1993) and BAP using the iron-oxide strip method (Sharpley, 1993). Analysis for DRP was performed according to the ascorbic acid method (Murphy and Riley, 1962). Samples were frozen until analyses were performed.

Natural runoff collectors (D. Côté, 1999, personal communication) were installed in all replications of the control, LPD-56, and HPD-56 treatments in early November 1999. These circular collectors consisted of aluminum edging (224-cm circumference × 10-cm high) inserted 5 cm into the soil, creating an internal area of 3971 cm^2. Polyethylene funnels (12.7-cm diam.) were placed inside a 12.7-cm diam. × 30-cm long PVC pipe that was installed flush with the soil surface at the downslope side of the plot frame, and the soil inside the pipe was removed. Fiberglass screening (2 mm) was placed inside each funnel to prevent clogging. The funnels and screening were attached with silicone caulk. Polyethylene tubing (2.5-cm diam.) connected the base of the funnel to a 19-L polyethylene bucket installed in a 90-cm deep excavation, located ≈60 cm downslope from the plot frames. A plastic cover was placed ≈4 cm above the funnels and drained outside the plot frame to prevent rainfall from falling directly into the funnels. Runoff was collected from the buckets within 2 d of each runoff event, total volumes were recorded, and a subsample was filtered through a 0.45-μm filter and analyzed for DRP.

Corn was planted at a density of 72 000 plants ha^{-1} on all plots following the June rainfall simulation in 1999 and in May 2000. Nitrogen fertilizer (as NH_4NO_3) was surface applied to all treatments at a rate of 180 kg N ha^{-1} immediately following planting. Glyphosate [N-(phosphonomethyl)glycine] was used to control weeds. All plants within each plot frame were cut near the base at physiological maturity and weighed, chopped, and subsampled to determine plant dry matter yield in 1999. Phosphorus uptake was calculated by multiplying the individual whole plant P concentration (Schulte et al., 1987) by the corresponding dry matter yield.

An analysis of variance was performed for treatment effects on antecedent soil moisture, surface residue cover, runoff amount, sediment, DRP, BAP, and TP concentrations and loads in runoff, distilled water extraction, Mehlich III, Bray-Kurtz P-1, ammonium oxalate P, P saturation, and silage yield, P concentration, and P uptake using PROC ANOVA (SAS Institute, 1992). Significant differences among treatment means were evaluated using a protected least significant difference (LSD) test at the 0.05 probability level.

RESULTS AND DISCUSSION

Manure Phosphorus Characterization

Phosphorus analyses on manures applied in the field experiment showed that all forms of P analyzed were higher in the HPD manure (Table 1). The addition of monosodium phosphate to achieve the high P diet resulted in more inorganic P in the HPD manure, as shown by the greater than two-fold increase in DI concentration. Bioavailable P concentrations were three times greater and TP concentrations were two times greater in the HPD manure compared with the LPD manure. Water soluble P and BAP were 40 and 69% of TP, respectively, for the HPD manure, and 29 and 43% of TP, respectively, for the LPD manure. These results indicate that excessive dietary P supplementation could exacerbate P losses in runoff where these manures are land-applied due to higher TP concentrations and higher proportions of TP in DI and BAP forms. Dry matter content of the high and low P manures was similar. Although the TP concentration in the high P manure analyzed from each plot was lower than the value from preliminary tests (8.9 vs. 12.8 g P kg^{-1}) used for determining P rate in manure application, treatment effects and their interpretation are not affected.

Site Characteristics and Measurements

Average time to runoff initiation in the simulated rainfall studies ranged from 5.7 to 7.2 min in June and 4.0 to 5.1 min in October, and treatments did not significantly affect time to runoff initiation (P = 0.48). Treatment effects on antecedent soil moisture content (0–2 cm) in June, 7 d following the manure application differed significantly (P = 0.01), ranging from 60 g kg^{-1} for the control to 205 g kg^{-1} for the HPD-56 treatment. The differences in soil moisture content were likely due to water added in the manure and/or decreased soil evaporation from the manured treatments due to their higher surface residue cover (Table 2). In October, antecedent soil moisture content ranged from 110 to 142 g kg^{-1} and was not significantly different among treatments. Soil bulk density measurements (0 to 2 cm) taken in October ranged between 1.33 to 1.46 g cm^{-3}, and showed no significant differences (P = 0.10) between treatments. Slope measurements in simulated rainfall plots ranged from 4.3 to 5.5% and did not differ significantly among manure treatments, confirming that slope

Table 2. Manure treatment effects on surface residue cover, runoff amount, and sediment and P concentrations in runoff following simulated rainfall, June 1999.†

			Concentration§				Load			
Treatment‡	Residue	Runoff	Sediment	DRP	BAP	TP	Sediment	DRP	BAP	TP
	%	mm	g L^{-1}	mg L^{-1}			kg ha^{-1}	g ha^{-1}		
Control	55b¶	3.4	2.2	0.03c	0.10	1.75b	84	1b	3	66b
LPD-56	81a	1.7	1.2	0.30c	0.61	1.61b	21	7b	9	31b
HPD-56	84a	2.7	1.6	2.84a	–††	6.71a	44	79a	–	194a
HPD-21	81a	2.0	1.8	1.18b	–	3.05b	37	26b	–	67b
					ANOVA					
$P > F$	0.01	0.32	0.70	<0.01	0.11	<0.01	0.18	<0.01	0.09	0.01
LSD (0.05)	17	NS#	NS	0.53	NS	2.16	NS	32	NS	92
CV, %	14	55	67	30	99	41	81	72	113	64

† Runoff was collected for 30 min after runoff initiation.
‡ Control, no manure; LPD-56, low P diet manure applied at 56 wet Mg ha^{-1} (40 kg P ha^{-1}); HPD-56, high P diet manure applied at 56 wet Mg ha^{-1} (108 kg P ha^{-1}); HPD-21, high P diet manure applied at 21 wet Mg ha^{-1} (40 kg P ha^{-1}).
§ DRP, dissolved reactive P; BAP, bioavailable P; TP, total P.
¶ Values within each column followed by the same letter are not significantly different based on Fisher's LSD (0.05) test.
# NS, not significant.
†† marks indicate that values for spring BAP soil tests are not reported.

was relatively uniform within the experimental site and did not contribute to treatment effects on P losses.

June Simulated Rainfall Study

Results from the June simulated rainfall showed that all manure treatments increased surface residue cover relative to the control (Table 2). Runoff amount and sediment concentration and load were not significantly affected by the treatments.

The HPD-56 and HPD-21 treatments increased DRP concentration in runoff relative to the control and LDP-56, and DRP concentration in HPD-56 was nearly 10 times higher than DRP concentration in LPD-56 (Table 2), even though the amount of P applied was only 2.5-fold greater in HPD-56. When the manures were applied at equivalent P rates, DRP concentration in runoff was about four times higher in the HPD-21 than from the LPD-56 treatment. Manure treatment effects on DRP load in runoff were similar to the concentration effects in that loads were significantly higher (≈11 times) in the HPD-56 compared with the LPD-56 treatment. The marked differences in runoff DRP concentrations and loads between the LPD-56 and HPD-56 treatments, even when the manures were applied at equal P rates, is likely due to differences in the P composition of the manures shown in Table 1.

The June runoff BAP data for the high P manure treatments are not shown in Table 2 because BAP values were lower than DRP values. Apparently, during the seven-month frozen sample storage period, a substantial portion of DRP reverted to P forms not measured as BAP. The runoff BAP data in Tables 2 and 3 could be affected by the same analytical problem as the omitted data. The BAP data are retained to point out the possible analytical problems with using the BAP method on stored unfiltered samples and to provide an estimate of runoff BAP levels in the experimental treatments. Treatment (control vs. LPD-56) effects on runoff BAP concentrations and loads were not significant.

Total P concentrations and loads in runoff in the HPD-56 treatment were significantly higher than in the other manure treatments and the control (Table 2). The TP load data appear to reflect P contributions from the manure additions and the influence of the manure treatments in controlling sediment loss. A comparison of sediment load and DRP load values in Table 2 indicates that most of the TP load in the control treatment appears to be associated with sediment loss, while a substantial portion of the TP load in the manured treatments is accounted for as DRP.

October Simulated Rainfall Study

Results from the October simulated rainfall application showed that the higher manure rate treatments (LPD-56 and HPD-56) still had significantly higher surface residue cover than the HPD-21 and control treatments (Table 3). Runoff amounts and sediment concentrations and loads were substantially higher in October than in June. Higher runoff amounts in fall vs. spring measurements have been reported in previous work (Mueller et al., 1984), and were attributed to lower infiltration rates due to lower surface residue cover and more extensive soil surface sealing in the fall (Bundy et al., 2001). The control had significantly higher runoff amounts than both the HPD-56 and the LPD-56 treatments, but the HPD-21 treatment was not significantly different from the other treatments. The control was about two times higher than the high manure rate treatments in sediment concentration and about five times higher in sediment load. This reflects the greater residue cover (as manure) and lower sediment loss in the manure treatments and is similar to the results of Mueller et al. (1984) and Bundy et al. (2001).

The DRP concentration in runoff was significantly higher (about four times) in the HPD-56 treatment compared with the LPD-56 and HPD-21 treatments (Table 3). Manure treatment effects on DRP load in runoff followed a similar trend, except that the HPD-21 treatment was not significantly different from the other treat-

Table 3. Manure treatment effects on surface residue cover, runoff amount, and sediment and P concentrations in runoff following simulated rainfall, October 1999.†

			Concentration§				Load			
Treatment‡	**Residue**	**Runoff**	**Sediment**	**DRP**	**BAP**	**TP**	**Sediment**	**DRP**	**BAP**	**TP**
	%	mm	g L^{-1}	mg L^{-1}			kg ha^{-1}	g ha^{-1}		
Control	43b¶	9.6a	8.2a	0.02b	0.15b	3.96	777a	2b	13	387a
LPD-56	57a	4.6b	3.2bc	0.21b	0.41b	2.53	156c	10b	19	116b
HPD-56	55a	4.2b	2.7c	0.89a	1.17a	3.16	126c	37a	49	141b
HPD-21	39b	8.0ab	5.8ab	0.21b	0.46b	3.22	435b	17ab	37	243ab
				ANOVA						
$P > F$	0.02	0.04	<0.01	<0.01	<0.01	0.09	<0.01	0.02	0.08	0.01
LSD (0.05)	12	4.1	2.7	0.31	0.41	NS#	226	21	NS	155
CV, %	15	39	33	59	46	21	38	80	63	44

† Runoff was collected for 30 min after runoff initiation.
‡ Control, no manure; LPD-56, low P diet manure applied at 56 wet Mg ha^{-1} (40 kg P ha^{-1}); HPD-56, high P diet manure applied at 56 wet Mg ha^{-1} (108 kg P ha^{-1}); HPD-21, high P diet manure applied at 21 wet Mg ha^{-1} (40 kg P ha^{-1}).
§ DRP, dissolved reactive P; BAP, bioavailable P; TP, total P.
¶ Values within each column followed by the same letter are not significantly different based on Fisher's LSD (0.05) test.
# NS, not significant.

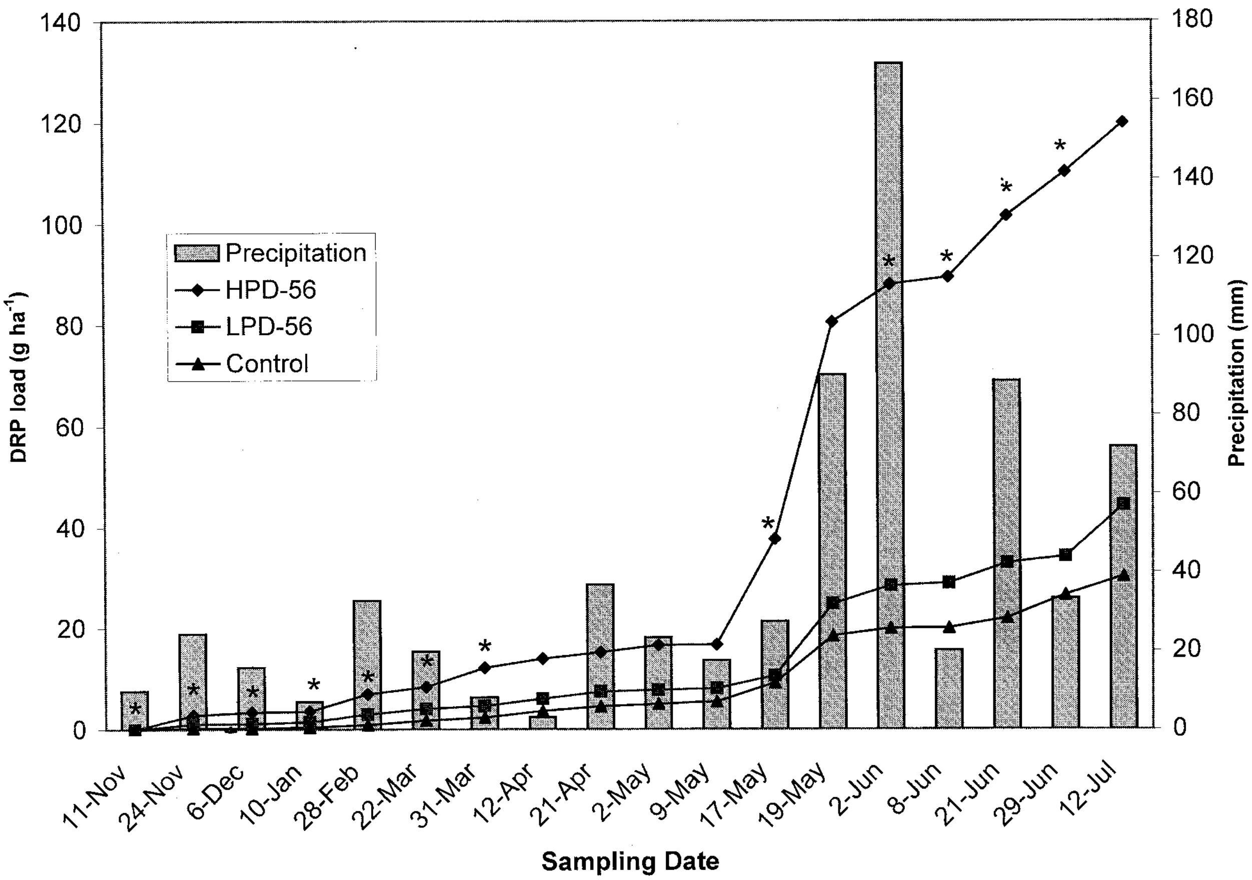

Fig. 1. Manure treatment effects on cumulative dissolved reactive P (DRP) load in natural runoff, November 1999 to July 2000. Asterisks indicate significant treatment differences (P =0.05) in cumulative DRP load, at the dates specified. LPD-56 = low P diet manure applied at 56 wet Mg ha^{-1}; HPD-56 = high P diet manure applied at 56 wet Mg ha^{-1}.

ments. The DRP load in runoff was nearly four times higher in the HPD-56 treatment compared with the LPD-56 treatment.

Treatment effects on BAP concentration were the same as for DRP concentration (Table 3). Runoff from the HPD-56 treatment was almost three times higher in BAP concentration than from the LPD-56 and HPD-21 treatments, but treatment effects on BAP load were not significant (P = 0.08).

In October, treatment effects on TP concentrations and loads were opposite from June (Tables 2 and 3). Concentrations and loads of TP in June were higher in the HPD-56 treatment than in the control and other treatments. However, in October, the control had a significantly higher TP load than the LPD-56 and HPD-56 treatments. This probably occurred because TP includes sediment bound P as well as dissolved P, and sediment losses in October were higher in the control and HPD-21 treatments (Table 3). The higher sediment losses are consistent with lower surface residue cover in those treatments. Total P loads were about three to five times higher in October than in June except for the HPD-56 treatment. The high June TP load in the HPD-56 treatment was largely due to the relatively high June DRP losses in that treatment. Higher October TP loads in the remaining treatments are consistent with higher runoff volumes and sediment concentrations in October.

Results from the October rainfall simulation show that manures from different dairy diet P concentrations still influenced P concentrations and loads in runoff more than four months after these manures were land-applied. This supports the results from the June data indicating that excess P in diets can increase DRP losses in runoff when manures from these diets are land-applied, and that this effect persists for at least several months. The influence of dietary P levels on TP losses in runoff is complicated by manure treatment effects on runoff volume and sediment loss.

Table 4. Climatological data showing departures from normal (30-yr average) for temperature and precipitation, Arlington, WI, November 1999 to July 2000 (National Climatic Data Center, Asheville, NC).

Month	Departures from normal	
	Temperature	Precipitation
	°C	mm
November	−3.7	−21
December	−2.0	−11
January	2.4	0
February	4.8	34
March	4.7	−13
April	−0.7	14
May	1.6	186
June	−0.8	90
July	−1.2	−21

Table 5. Mean soil test P values in June and treatment effects on soil test P values in October using several extraction methods (0- to 2-cm depth), 1999.

Month	Treatment†	DI	M3	Bray	BAP	AOX-P	P-SAT
		Soil P extraction method‡					
		mg P kg^{-1}					%
June	Control§	0.5	21	14	28	172	11
October	Control	1b¶	16b	15b	27b	143	9
	LPD-56	2b	26b	20b	31b	146	9
	HPD-56	7a	62a	50a	63a	190	11
	HPD-21	2b	33b	26b	38b	148	9
		ANOVA					
$P > F$		<0.01	<0.01	<0.01	<0.01	0.09	0.11
LSD (0.05)		2	20	14	17	NS#	NS
CV, %		52	37	33	27	16	16

† Control, no manure; LPD-56, low P diet manure applied at 56 wet Mg ha^{-1} (40 kg P ha^{-1}); HPD-56, high P diet manure applied at 56 wet Mg ha^{-1} (108 kg P ha^{-1}); HPD-21, high P diet manure applied at 21 wet Mg ha^{-1} (40 kg P ha^{-1}).
‡ DI, distilled water; M3, Mehlich 3; Bray, Bray-Kurtz P-1; BAP, bioavailable P (iron oxide strip); AOX-P, ammonium oxalate P; P-SAT, P saturation.
§ Mean values for control plots in June 1999.
¶ October values within each column followed by the same letter are not significantly different based on Fisher's LSD (0.05) test.
# NS, not significant.

Natural Runoff Study

Treatment effects on DRP losses in natural runoff (Fig. 1) support the simulated rainfall results. The cumulative DRP load is consistently higher in the HPD-56 treatment than the LPD-56 treatment and control. Precipitation events varied between 3 and 169 mm (Fig. 1) and runoff volumes ranged from 0.02 to 10.39 mm (data not shown). January to March runoff events were primarily associated with snowmelt, and monthly temperatures were above average for this period (Table 4). The months of May and June received unusually large precipitation amounts (Table 4), resulting in much larger runoff volumes than in previous rainfall events and treatment effects on DRP load were accentuated in these cases. Individual events did not always cause significant differences in DRP concentration and load, due to the variability of the data. The CV for cumulative DRP load ranged from 55 to 80%. There were significant treatment differences ($P = 0.05$) in cumulative DRP load at 67% of the individual events (12 out of 18 dates). For nine of these dates, the HPD-56 treatment was significantly higher than the LPD-56 treatment and the control, for three of those dates (10 January, 22 and 31 March) the HPD-56 treatment was similar to the LPD-56 treatment but significantly higher than the control. If significance was broadened to the 0.10 level, 15 out of 18 dates had significant treatment effects on cumulative DRP load. Overall, the data confirm that higher amounts of DRP are lost from plots amended with high P diet manure than plots amended with low P diet manure, and these effects on cumulative DRP loss persist for at least 1 yr.

Soil Phosphorus Measurements

The mean soil test P values (0 to 2 cm) for the experimental area indicate a relatively low initial soil P status (Table 5). At the 0- to 15-cm soil depth, the Bray-Kurtz P-1 soil test P level was 11 mg kg^{-1}, and P additions would be recommended for production of most crops at this initial soil test level (Kelling et al., 1998). The October soil test P results show that the HPD-56 treatment usually increased soil test P values at the 0- to 2-cm depth. When the high P and low P manures were applied at the same rate (HPD-56 and LPD-56), Bray-Kurtz P-1 in the high P treatment increased by more than two-fold compared with the LPD-56 treatment. When the high P manure was applied at the same P rate as the low P manure (HPD-21 and LPD-56), Bray-Kurtz P-1 tests were not significantly different. This was also true for the distilled water, Mehlich III, and BAP tests, which showed a two- to three-fold increase in the HPD-56 treatment compared with the LPD-56 and HPD-21 treatments.

Corn Yield and Phosphorus Uptake

Although not significant at the $P = 0.05$ level, total aboveground corn dry matter yield ($P = 0.08$) and plant P concentration ($P = 0.06$) were increased by the manure treatments (Table 6). These responses are consistent with the application of P to a soil testing low in plant available P. In addition, total plant P uptake

Table 6. Manure treatment effects on dry matter yield, P concentration, and P uptake in corn, 1999.

Treatment†	Dry matter yield	P concentration	P uptake
	kg ha^{-1}	g kg^{-1}	kg P ha^{-1}
Control	8 196	2.0	15b‡
LPD-56	12 666	2.4	26a
HPD-56	10 992	2.3	23a
HPD-21	11 502	2.4	24a
	ANOVA		
$P > F$	0.08	0.06	0.01
LSD (0.05)	NS§	NS	6
CV, %	20	8	18

† Control, no manure; LPD-56, low P diet manure applied at 56 wet Mg ha^{-1} (40 kg P ha^{-1}); HPD-56, high P diet manure applied at 56 wet Mg ha^{-1} (108 kg P ha^{-1}); HPD-21, high P diet manure applied at 21 wet Mg ha^{-1} (40 kg P ha^{-1}).
‡ Values within each column followed by the same letter are not significantly different based on Fisher's LSD (0.05) test.
§ NS, not significant.

in the manure treatments was significantly greater than in the control. Since a uniform N addition was made to all treatments, these responses are most likely due to P applied in the manures. The possibility of other manure treatment effects on responses shown in Table 6 cannot be conclusively excluded. In contrast to the runoff P data, corn yields and total plant P uptake and concentration did not differ among the high and low P manure treatments regardless of manure application. This suggests that the lowest P rate added in manure (40 kg P ha^{-1}) supplied adequate P to maximize dry matter yield and plant P concentration.

CONCLUSIONS

Phosphorus concentrations in dairy diets influence the forms and amounts of P in manure. Results from this study indicate that when manures from dairy cows fed different dietary P levels are land-applied, a high P diet manure contributes more P to runoff than a low P diet manure, in both simulated and natural runoff. This effect was seen even when the manures were applied at the same P rate. In June, DRP concentration in runoff from the high P diet manure was nearly 10 times higher than the low P diet manure when manures were applied at the same manure rate (2.84 vs. 0.30 mg L^{-1}), and four times higher when applied at equivalent P rates (1.18 vs. 0.30 mg L^{-1}). In October, the same comparisons showed that at equivalent manure rates, DRP concentrations were nearly four times higher in the high P diet manure treatment (0.89 vs. 0.21 mg L^{-1}) and the same when applied at equivalent P rates (0.21 mg L^{-1}). Dissolved reactive P measurements in natural runoff support the simulated runoff data. These data emphasize the need to avoid excess P supplementation of dairy cow diets to minimize P additions from land-applied manure and reduce P losses to surface runoff and adverse effects on water quality. Regardless of whether an N-based (same manure rate) or P-based (same P rate) manure application strategy is followed, this study indicates that excess P in dairy diets increases the risk of P loss in runoff from land-applied manure. These findings indicate that P in animal diets and its influence on manure P characteristics should be considered when applying the P-index and when implementing nutrient management plans.

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REFERENCES

Brodison, J.A., E.A. Goodall, J.D. Armstrong, D.I. Givens, F.J. Gordon, W.J. McCaughey, and J.R. Todd. 1989. Influence of dietary phosphorus on the performance of lactating dairy cattle. J. Agric. Sci. (Cambridge) 112:303–311.

Bundy, L.G., T.W. Andraski, and J.M. Powell. 2001. Management practice effects on phosphorus losses in runoff in corn production systems. J. Environ. Qual. 30(in press).

Carpenter, S.R., N.F. Caraco, D.L. Correll, R.W. Howarth, A.N. Sharpley, and V.H. Smith. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecol. Applic. 8:559–568.

Daniel, T.C., A.N. Sharpley, D.R. Edwards, R. Wedepohl, and J.L. Lemunyon. 1994. Minimizing surface water eutrophication from agriculture by phosphorus management. J. Soil Water Conserv. Suppl. 49:30–38.

Dixon, R.M., and A.E. Peterson. 1968. A vacuum system for accumulating runoff from infiltrometers. Soil Sci. Soc. Am. Proc. 32:123–125.

Frank, K., D. Beegle, and J. Denning. 1998. Phosphorus. p. 21–26. *In* J.R. Brown (ed.) Recommended chemical soil test procedures for the North Central Region. NC Regional Res. Publ. no. 221. Missouri Agricultural Experiment Station, Columbia, MO.

Huff, F.A., and J.R. Angel. 1992. Rainfall frequency atlas of the midwest. Bull. 71. Illinois State Water Survey, Champaign, IL.

Kelling, K.A., L.G. Bundy, S.M. Combs, and J.B. Peters. 1998. Soil test recommendations for field, vegetable and fruit crops. Univ. of Wisconsin Ext. Publ. A2809. Univ. of WI Ext., Madison, WI.

Khoransani, G., R. Janzen, W. McGill, and J. Kenelly. 1997. Site and extent of mineral absorption in lactating cows fed whole crop cereal grain silage or alfalfa silage. J. Anim. Sci. 75:239–248.

McDowell, L.R. 1992. Minerals in animal and human nutrition. Academic Press, San Diego, CA.

Meyer, L.D., and W.C. Harmon. 1979. Multiple-intensity rainfall simulator for erosion research on row sideslopes. Trans. ASAE 22:100–103.

Mehlich, A. 1984. Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. Commun. Soil Sci. Plant Anal. 15:1409–1416.

Metcalf, J.A., R.J. Mansbridge, and J.S. Blake. 1996. Potential for increasing the efficiency of nitrogen and phosphorus use in lactating dairy cows. J. Anim. Sci. 62:636.

Morrison, J.E., Jr., K.N. Potter, H.A. Torbert, and D.J. Pantone. 1996. Comparison of three methods of residue cover measurements on rainfall simulator sites. Trans. ASAE 39:1415–1417.

Morse, D., H. Head, C. Wilcox, H. Van Horn, C. Hissem, and B. Harris, Jr. 1992. Effects of concentration of dietary phosphorus on amount and route of excretion. J. Dairy Sci. 75:3039–3049.

Mueller, D.H., R.C. Wendt, and T.C. Daniel. 1984. Soil and water losses as affected by tillage and manure application. Soil Sci. Soc. Am. J. 48:896–900.

Murphy, J., and J.R. Riley. 1962. A modified single solution method for the determination of phosphate in natural waters. Anal. Chem. 27:31–36.

National Research Council. 1989. Nutrient requirements of dairy cattle. 6th ed. Natl. Acad. Sci., Washington, DC.

Pierzynski, G.M. (ed.) 2000. Methods of phosphorus analysis for soils, sediment, residuals, and waters. South. Coop. Series Bull. 39:31–34.

Pote, D.H., T.C. Daniel, A.N. Sharpley, P.A. Moore, Jr., D.R. Edwards, and D.J. Nichols. 1996. Relating extractable soil phosphorus to phosphorus losses in runoff. Soil Sci. Soc. Am. J. 60:855–859.

SAS Institute. 1992. SAS/STAT user's guide. Release 6.03, 4th ed. SAS Inst., Cary, NC.

Satter, L.D., and S. Wu. 1999. Reducing manure phosphorus by dairy diet manipulation. Proc. Wis. Fert. Aglime Pest Mgmt. Conf. 38:183–192.

Schulte, E.E., J.B. Peters, and P.R. Hodgson. 1987. Wisconsin procedures for soil testing, plant analysis, and feed and forage analysis. Soil Fertility Series no. 6. Dep. of Soil Science, Univ. of Wisconsin, Madison, WI.

Sharpley, A.N. 1993. An innovative approach to estimate bioavailable phosphorus in agricultural runoff using iron oxide-impregnated paper. J. Environ. Qual. 22:597–601.

Sharpley, A.N., S.C. Chapra, R. Wedepohl, J.T. Sims, and T.C. Daniel. 1994. Managing agricultural phosphorus for protection of surface waters: Issues and options. J. Environ. Qual. 23:437–451.

Ternouth, J.H. 1989. Endogenous losses of phosphorus by sheep. J. Agric. Sci. 113:291–297.

USEPA. 1993. Methods for the determination of inorganic substances in environmental samples. EPA/600/R-93/100. Method 365.1. U.S. Gov. Print. Office, Washington, DC.

Valk, H., J.A. Metcalf, and P.J.A. Withers. 2000. Prospects for minimizing phosphorus excretion in ruminants by dietary manipulation. J. Environ. Qual. 29:28–36.

Wu, Z., L.D. Satter, and R. Sojo. 2000. Milk production, reproductive performance, and fecal excretion of phosphorus by dairy cows fed three amounts of phosphorus. J. Dairy Sci. 83:1028–1041.

Zemenchik, R.A., N.C. Wollenhaupt, K.A. Albrecht, and A.H. Bosworth. 1996. Runoff, erosion, and forage production from established alfalfa and smooth bromegrass. Agron. J. 88:461–466.

Bermudagrass Management in the Southern Piedmont USA. II. Soil Phosphorus

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ABSTRACT

Plant production can be limited by low levels of available P due to high P-fixation capacity in soils of the southeastern USA. On the other hand, there is increasing concern about excessive application of P to soil, especially when manure application is based upon N content. We evaluated changes in Mehlich-I extractable soil P during 5 yr of bermudagrass [*Cynodon dactylon* (L.) Pers.] management varying in fertilization [inorganic and broiler chicken (*Gallus gallus*) litter] and harvest strategy (unharvested, low and high cattle (*Bos taurus*) grazing pressure, and haying). Broiler litter supplied eight times more P than inorganic fertilization to meet the N requirement. At a depth of 0 to 6 cm, Mehlich-I extractable soil P increased 0.8 $\pm$ 1.6 mg kg^{-1} yr^{-1} (4 $\pm$ 8% of total P added) with inorganic-only fertilization, 2.4 $\pm$ 3.0 mg kg^{-1} yr^{-1} (9 $\pm$ 11% of total P added) with clover (*Trifolium incarnatum* L.) cover crop plus inorganic fertilization, and 8.7 $\pm$ 9.8 mg kg^{-1} yr^{-1} (6 $\pm$ 7% of total P added) with broiler litter. Haying kept Mehlich-I extractable soil P constant with time due to removal of P with harvest of biomass. At the end of 5 yr of broiler litter application to grazed land, Mehlich-I extractable soil P was 135, 50, 22, and 4 mg kg^{-1} higher than with inorganic fertilization at depths of 0 to 3, 3 to 6, 6 to 12, and 12 to 20 cm, respectively. Broiler litter fertilization was effective at increasing Mehlich-I extractable soil P to an agronomically productive level (50 to 60 mg kg^{-1} 15 cm^{-1}), but continued application could lead to excessive P accumulation that could threaten water quality from surface runoff unless appreciable soil fixation or removal of forage biomass were to occur.

Lateral and vertical distribution of nutrients in pastures can either limit plant-animal productivity or pose environmental threats, depending upon quantities available and the type of management employed. In the southeastern USA, rainfall is abundant and soils are weathered, which make nutrient applications susceptible to both runoff and leaching losses. The eroded and weathered soils of the southeastern USA, in general, are low in available P, with applied P quickly fixed into unavailable forms upon exposure to clay-sized minerals (Anderson et al., 1996). Crop responses to fertilizer application of P are generally large, but repeated applications are necessary because of the high anion adsorption capacity of these soils, particularly in the clayey subsoil, which can become exposed at the soil surface from a long history of erosion (Bruce et al., 1990).

Poultry production in the Appalachian Piedmont is extensive (U.S. Dep. of Commerce, 1992). Manure mixed with bedding material (i.e., litter) at the end of the production cycle is cleared from confinement housing and applied to nearby land as a source of valuable nutrients for crop and pasture production. Depending upon management, however, repeated application of poultry litter to the same land could become a source of excessive nutrients that would threaten water quality (Sharpley et al., 1993; Kingery et al., 1994). Environmental regulations to protect water quality have and will continue to be developed, especially with the increased competition for water resources among agricultural-, urban-, wildlife-, and recreational-supporting sectors of our increasingly affluent society. Unfortunately, details on nutrient accumulation and distribution in soils managed for pasture production with differences in harvest strategy are limited. Such information is necessary for legislators to make rational decisions on land use and nutrient management based on scientific evidence.

Grazing of a forage crop compared with haying returns most of the manure directly to the land, which affects nutrient distribution in soil (Haynes and Williams, 1993; Follett and Wilkinson, 1995). Animal behavior patterns in pastures suggest that preferential deposition of feces and urine near shade and water sources would lead to a non-uniform distribution of nutrients (Mathews et al., 1996). Further, the impact of whether forage is mechanically harvested or not on total and extractable soil P deserves attention, based on the extent of land currently managed under the Conservation Reserve Program. Harvest management would be expected to alter the depth distribution of extractable soil P, because of the presence of animal traffic, ruminant processing of forage (i.e., biological transformation of nutrients), or nutrient removal in hay.

We hypothesized that with equivalent amounts of total N applied, fertilization strategy (i.e., inorganic or organic with differences in associated P content) could affect the availability of P to forage and its form and depth distribution in soil. Our objective was to characterize the temporal and spatial distribution of Mehlich-I extractable soil P in response to differences in fertiliza-

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Abbreviations: ICPS, inductively coupled plasma spectroscopy.